UNIVERSAL DESIGN METHOD THAT CONSIDERS PHYSICAL BURDEN THROUGH THE APPLICATION OF A DIGITAL HUMAN MODEL: CASE STUDY OF A WORKING TABLE

T. Nakajima, M. Shimada and M. Inoue

Department of Mechanical Engineering Informatics, Meiji University, 1-1-1 Higashi-Mita, Tama-Ku, Kawasaki 214-8571, Japan.

Corresponding Author's Email: ce182044@meiji.ac.jp

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ABSTRACT: Recently, owing to aging and internationalization, the concept of universal design aimed at satisfying various users has attracted attention. However, the concept and definition of universal design varies between countries or companies, and a general approach to such design has yet to be established. Moreover, it is not clear how to take users' physical characteristics and feelings when using a product into consideration. Therefore, in this research, the authors propose a universal design method that considers the user's physical burden by applying a digital human model. First, the authors divide design variables into designer-controllable and uncontrollable factors. Next, based on the human characteristics database, design variables and constraint conditions are defined as range values. Then, an interval operation is performed using aforementioned ranged value and a relational expression between a design variable and a constraint condition, and a design solution is derived as a set. Furthermore, based on the derived design solution sets, the authors simulate use of a product by a digital human model. Finally, by evaluating physical load, the authors derive a design solution that takes account of the user's physical burden, using a working table as a case study.

KEYWORDS: *Universal Design; Digital Human Model; Physical Burden; Design Solution Sets*

1.0 INTRODUCTION

In the past, companies that design multifunctional, high-quality products have tried to differentiate their products from their competitors using high technology. However, in recent years, users' needs have diversified against the background of aging and internationalization, so it is necessary to design products not only for technical strength, but also for diverse users. Therefore, product design emphasizing user satisfaction and feelings of use and product quality is required. Hence, the concept of universal design (UD) aimed at satisfying diverse users has attracted attention [1]. To realize UD, it is necessary to understand the physical characteristics and demands of diverse users, and to derive the corresponding design values. However, the concept and definition of UD varies between countries and companies. Therefore, general methods of UD have yet to be established, and designers derive solutions by trial-and-error repetition of design, prototyping, evaluation, and improvement of products based on past experience. One factor affecting user satisfaction is the load that the product imposes upon the user's body. Therefore, research on product design using biometric measurements such as electromyograms has been conducted for the purpose of quantitatively evaluating ease of use and comfort when using the product [2-3]. However, this evaluation method is performed after the product has already been manufactured, making improvements costly and time-consuming. Moreover, the burden imposed on the subject by biometric measurement is large. Therefore, an evaluation method based on efficient physical loading is required.

Human-Centered Design (HCD) is one conventional design process for emphasizing users. HCD is a design process defined by ISO9241-210 of the International Organization for Standardization [4]. In HCD, a product is designed according to the user's request and the user can obtain a high level of satisfaction. Therefore, it has been used to propose product-development methods based on evaluating the usability of medical equipment [5] and designing pillows that users can easily turn over [6]. However, there has been no discussion of countermeasures considering a large but unspecified number of users, or the physical load on the user when employing a product. Therefore, in addition to emphasizing users, design methods must satisfy diverse users and consider feelings of physical burden. Thus, in this study, the authors propose a UD method that considers physical burden feeling using a digital human model (DHM). The DHM can reproduce the user's attitude and motion when the using the product on the computer and analyze it by simulation. Compressive force, joint moment, and other considerations can be derived from the set attitude, such that the relationship between the user and the product can be expressed quantitatively. Thus, interior design of passenger cars using DHM [7] and research on usability evaluation of residential-facility equipment is also being conducted by companies [8]. In this research, it is possible to evaluate the physical burden feelings of diverse users from the load on the user's body. Since these feelings can be predicted at the initial stage of design, the number of prototypes of the product can be reduced. Therefore, efficient product design with reduced developmental period and cost can be expected. The DHM software used in this research is the 3D Static Strength Prediction Program (3DSSPP), developed at the Center for Ergonomics at the University of Michigan, USA. This software is used by more than 2,000 international companies as well as studies of the burden on the human body [9-10]. Also, 3DSSPP specializes in analysis of handling material handling work. Furthermore, it is most useful in the analysis of the "slow" movements used in heavy materials handling tasks since the biomechanical computations assume that the effects of acceleration and momentum are negligible [11-12]. Thus, Tecnomatix Jack, Delmia and IMMA are used as research on DHM [13-14], but 3DSSPP was chosen in this study because it is assumed to be a user who manually works on the work-table. In the proposal method of this study, the product information and the physical diversity of users is represented by a range value, and a design solution that satisfies the constraint condition is derived. Then, based on the obtained design solution sets, the authors evaluate the physical burden feeling of the user's posture using DHM and propose a UD method to consider this feeling. Moreover, the effectiveness of the proposed method is shown by applying it to the design of a working table.

2.0 UNIVERSAL DESIGN METHOD USING A DIGITAL HUMAN MODEL

Figure 1 shows the flow chart of the proposed method.

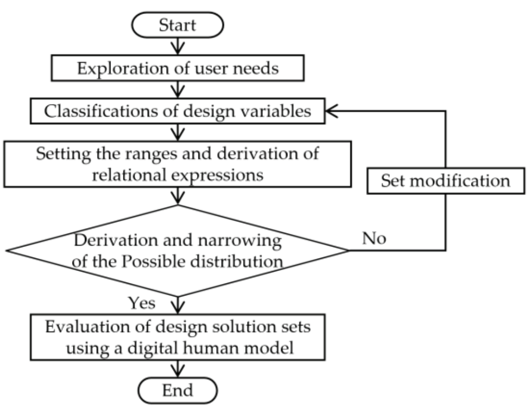


Figure 1: Flowchart of proposed universal design method

2.1 Extraction of User Needs

The designer extracts the factors affecting user satisfaction and defines them as a constraint condition. This condition assumes that the user can minimally use the product. This is set assuming physical limits such as joints when using products. User needs can be extracted using evaluation-grid or rating-scale methods. Design information related to extracted user needs is defined as a design variable.

2.2 Classifications of Design Variables

When performing UD, it is necessary to consider information that cannot be freely set by the designer, such as human body characteristics. Therefore, values expressing characteristics such as body height and weight are treated as design variables similar to product dimensions. Thus, it is possible to better consider the physical characteristics of the user in a design. In this research, design variables are classified into two types: control factors and uncontrollable factors. The former can be freely changed by the designer and includes the size and mass of the product. The latter cannot be changed freely and expresses body height and weight.

2.3 Setting the Ranges and Derivation of Relational Expressions

In this process, design variables and constraints are represented as ranges, and relational expressions are derived between them. The range of the design variables is defined based on product information such as size and weight, as well as measured values of body characteristics such as height and weight. Moreover, the constraint conditions are added based on ergonomic data such as the range of motion of a human joint. To derive the relational expression, we first show the product and user's posture in the model diagram for the set design variables and constraint conditions. Then, relational expressions between these quantities are derived by trigonometric functions and the moment of force. Another method is used to calculate data by the design of experiments and to derive the relational expression using the response surface method.

2.4 Derivation and Narrowing of the Possibility Distribution

In this process, the possibility distribution is derived by interval arithmetic and narrowed down. The designer derives this distribution using the relational expression derived in Section 2.3. Next, when there is a range in which the distribution does not satisfy the constraint condition, it is narrowed down. The narrowing method divides the range of design variable, and the possibility distribution is derived with the combination of the divided design variables again. Then, it is evaluated whether the range of the constraint condition is satisfied or not, and the range not satisfying the constraint condition is deleted. As a result, a design solution sets satisfying the constraint condition is obtained. However, among the design variables classified in Section 2.2, the uncontrollable factor represents the physical characteristics of the user. Therefore, based on the definition of UD used in this research such as "to satisfy all users" which the designer does not divide the uncontrollable factor. We divide only the control factors that the designer can freely set and derive a new possibility distribution. Figure 2 shows a conceptual diagram of the narrowing of the design solution sets.

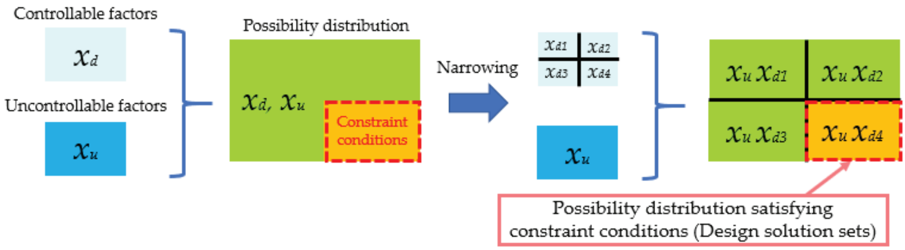


Figure 2: Conceptual diagram of the narrowing of design solution sets

2.5 Evaluation of Design Solution Sets using a Digital Human Model

Based on the design solution sets obtained in Section 2.4, the DHM is used to evaluate the physical burden of the user when utilizing the product. At this time, the designer evaluates the solution sets with the arbitrary physical burden indices as the performance requirements. Specifically, a DHM is created on the computer from the derived design solution sets to represent the posture when using the product. The compressive force to the waist, joint moment and %MVC are computed by simulation analysis. From each calculated value, 10 points are assigned to the combination of design variables having the smallest value and 1 point is assigned to the combination of variables with the largest one, and the evaluation is performed in 10 steps. At this time, by visualizing the corresponding range solution with a color chart, the designer clarifies the more preferable solution sets out of all those derived.

Thus, the design solution satisfies the constraint condition and the combination of design variables with the all high evaluation is deriven as the design solution. Also, when the derived design solution set does not satisfy the set evaluation, the definitions and ranges of the design variables and constraint conditions in Sections 2.2 and 2.3 are modified and a design solution sets are derived again.

3.0 CASE STUDY: WORK-TABLE HEIGHT

Working tables, such as those in kitchens and washrooms, are essential to living in houses. In addition, factories often use work tables, which are easy to move because there are no chairs, for line work. However, a long time spent standing to work causes muscle fatigue and lower-back pain as muscles compress blood vessels and blood flow deteriorates. Therefore, it is necessary for the user to select an appropriate work-table height. Studies on ideal work-table height have been pursued for over 30 years, but the physical burden on a user when utilizing the product has not been discussed [15-16]. In this research, we apply the proposed design method to select the height of a table used by multiple workers.

3.1 Extraction of User Needs

The authors define the target users and constraint condition. When the work table is high, stiff shoulders arise due to raised arms; when the work table is low, lower-back pain occurs due to bending of the waist. Therefore, work-table height is greatly related to body height. For this study, the worker using the table was defined as a female user with a body height in the range of [1,338, 1,673] mm (such the range included in the human-characteristics database). In addition, as shown in Figure 3, a model diagram of the posture when using the work table is assumed. Furthermore, the constraint condition was defined as the waist range of motion, θ.

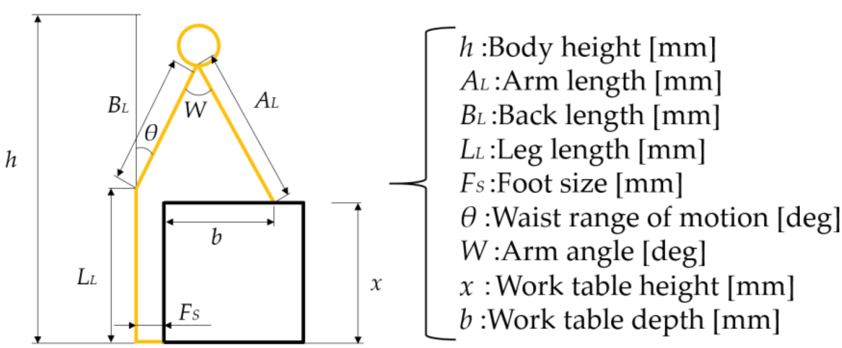


Figure 3: Posture model for the work table

3.2 Classifications of Design Variables

Next, the authors classify the design variables into two types, control factors and uncontrollable factors. The control factors were work-table height x [mm], depth b [mm] and arm angle W [deg]. The uncontrollable factor was body height h [mm].

3.3 Setting the Ranges of Design Variables and Constraint Conditions: Derivation of Relational Expressions

The authors defined the range values of control factors with reference to the dimensional standard of kitchen equipment (JIS A 0017). Moreover, body height h was defined based on its actual measured value. The range value of the constraint condition is set as the user's range of motion; when using the work table, this range is to be satisfied. Table 1 shows the range of each design variable and the constraint condition. Also, it shows the relationship between factors and levels. Equations (1) and (2) show relational expressions for the design variables and constraint condition. Here, the arm length A_L [mm], the back length B_L [mm] and the leg length L_L [mm] were strongly correlated with the body height h from the human characteristics database. Therefore, approximate expressions of A_L, B_L and L_L are shown in Equations (3), (4) and (5). The foot size, F_S [mm], was calculated from the human characteristics database by the mean value (=224 mm). Then, it was set as a fixed value.

$$x = L_L + H_L \cos\theta - A_L \cos(W - \theta) \tag{1}$$

$$b = H_L \sin\theta + A_L \sin(W - \theta) - F_S \tag{2}$$

$$A_L = 0.306h + 200.080 \tag{3}$$

$$B_L = 0.4057h - 51.834 \tag{4}$$

$$L_L = 0.4688h + 9.554 \tag{5}$$

Next, to derive the relational expression for the waist-movement range θ (which is a constraint condition), the authors created an orthogonal-array table using the experimental design method. The values corresponding to each level are substituted into the created L_9 (3^4) orthogonal table, and the values of work-table height x and depth b calculated from the Equations (1) and (2) are shown in Table 2. In addition, θ in Table 2 and x, b were exchanged. Therefore, from the factor (x, b, W, h) and the experimental data (θ), the relational expression for the waist-motion range $\theta = f(x, b, W, h)$ was derived using the response surface method. The obtained expression is abbreviated due to lengthy.

Table 1: Ranges of design variables and constraint conditions

Type	Name	Value (Level)
Design variable	Body height: h [mm]	1338 1509.5 1681
	Work table height: x [mm]	Constraint [800, 1100]
	Work table depth: b [mm]	Constraint [0, 600]
	Arm angle: W [deg]	0 45 90
Constrained condition	Waist range of motion: θ [deg]	0 45 90

Table 2: Relationship between the L_9 (3^4) orthogonal arrays x and b

	h	W	θ	x [mm]	b [mm]
Experiment 1	1338	0	0	518	-224
Experiment 2	1338	45	45	374	123
Experiment 3	1338	90	90	27	267
Experiment 4	1509.5	0	45	645	-296
Experiment 5	1509.5	45	90	249	-132
Experiment 6	1509.5	90	0	1278	438
Experiment 7	1681	0	90	798	-308
Experiment 8	1681	45	0	923	281
Experiment 9	1681	90	45	738	727

3.4 Derivation and Narrowing of the Possibility Distribution

Interval arithmetic is performed using the conditions defined above, and design solution sets satisfying the constraint conditions are derived. As a result of the interval operation, 512 sets were derived of these, 115 satisfied the constraint conditions. These represent work-table heights that can be used by all target users.

3.5 Evaluation of the Design Solution Sets using the Digital Human Model

Finally, based on the obtained design solution sets, the authors create a DHM to simulate posture when using the table, and then evaluate the feeling of physical burden. In consideration of back pain and shoulder stiffness when using a work table, the authors added evaluation indices from the fourth to fifth intervertebral disks (L4/L5) and from the fifth disk to the first sacral vertebra (L5/S1), as well as considering the moment M of the shoulder joint with respect to the arm angle W. Equations (6), (7), (8), (9), (10) and (11) are approximated expressions for each evaluation index:

$$F_{L4/L5(\mathrm{min})} = -0.0226\theta^2 + 6.4145\theta + 103.43 \tag{6}$$

$$F_{L4/L5(\mathrm{max})} = -0.0226\theta^2 + 7.5928\theta + 95.725 \tag{7}$$

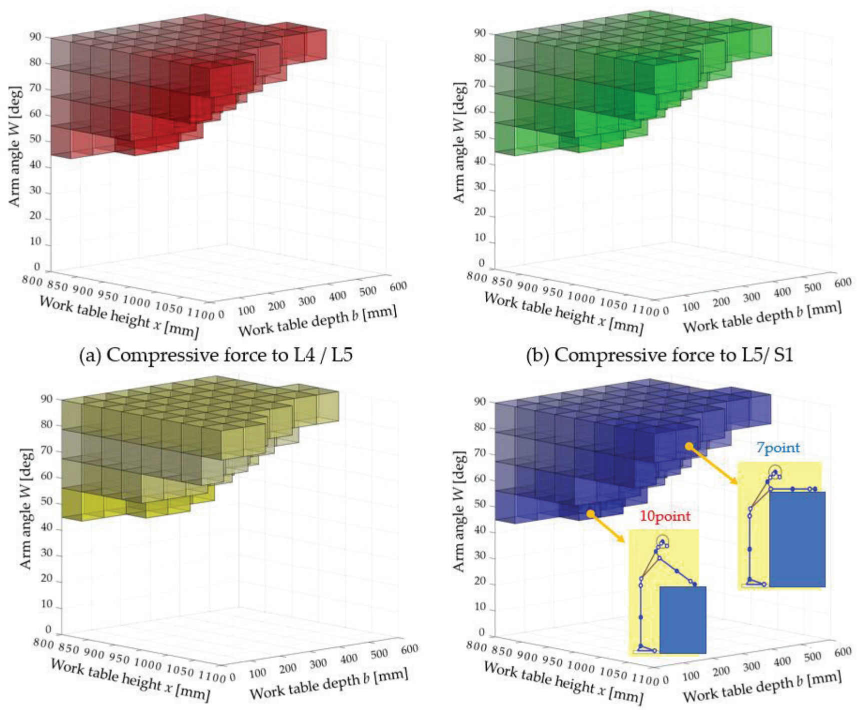
$$F_{L5/S1(\mathrm{min})} = -0.0162\theta^2 + 6.2145\theta + 110.37 \tag{8}$$

$$F_{L5/S1(\mathrm{max})} = -0.0616\theta^2 + 7.6375\theta + 99.567 \tag{9}$$

$$M_{(\min)} = 0.0003W^2 - 0.7614W - 4.2337 \tag{10}$$

$$M_{(\min)} = 0.0227W^2 - 3.3602W + 67.872 \tag{11}$$

From the data obtained from the above evaluation indices was divided 10, the comfort felt by the user was quantitatively evaluated. The range and evaluation are considered of each evaluation index. The higher the evaluation, the lower the physical burden on the user. In addition, data were calculated at the minimum and maximum values of the waist's movable range θ in each solution set, and the average was used as the evaluation value. The solution sets (a), (b) and (c) evaluated by the DHM and the design solution set (d) and the attitude of the user, which comprehensively summarize each evaluation indicator, are shown in Figure 4. Figure 4 shows the combination of design variables with higher evaluation value in the darker the color of blocks). The design solution sets that are most favorably evaluated fall in waist range of motion [0.2, 25.7] deg when the work-table height is [837.5, 875.0] mm, the depth is [225, 300] mm, and the arm angle is [45.00, 56.25] deg. In these sets, all evaluation indices were 10 points, and the results with the smallest physical loads on all target users were obtained.



(a) Compressive force to L4 / L5
(b) Compressive force to L5/ S1
(c) Moment of shoulder joint
(d) Comprehensive evaluation

Figure 4: Design solution sets of working tables

3.6 Results and Discussion by the Proposed Method

As shown in Figure 4, it is necessary to set the arm angle to 45 degrees or more. This is because it is considered the angle required for a short user to reach the minimum work-table height of 800 mm. Therefore, as the work-table-height increases therefore, the arm angle also increases. In addition, evaluation of the compressive forces acting on L4/L5 and L5/S1 that evaluation of the design solution sets becomes high as the work-table height increases and depth decreases. This means that when the work table is low and wide, a user must bend at the waist to reach it. However, if the work table is high and narrow, since the user may increase their arm angle without bending their waist, the compressive forces to L4/L5 and L5/S1 become small, evaluation of the design solution sets are considered high.

Furthermore, evaluating the solution sets in terms of moment to the shoulder joint shows that low evaluations are obtained for the combination of design variables for which the angle of the arm becomes large. This is because short users need to raise their arms to reach the work table as its height increases. Therefore, the moment of the shoulder joint is considered to be large. Figure 4 shows that short users need to raise their arms as the work-table height increases. Also, tall users need to bend at their waist when the work table is low and wide. Therefore, the physical burden on the waist may conceivably become large. Thus, the best-rated solution set is x [837.5, 875.0] mm, b [225, 300] mm and W [45.00, 56.25] mm. This is because the arm angle is in the range where the moment of the shoulder joint is lowest and the work-table height and depth are such that users mostly do not need to bend at the waist. While we considered only female users in the DHM, the design solution set for men can be obtained in the same way. As explained above, the physical diversity of users is expressed in terms of the range value. By evaluating the sense of physical burden using the DHM for the obtained design solution sets, we confirmed that it was possible to design a work-table height that diverse users can comfortably use.

4.0 CONCLUSION

In this research, users' diverse physical characteristics were expressed as range information in addition to the parameters of the product itself, and the feeling of physical burden was evaluated using a DHM for the obtained design solution sets. The authors proposed a UD method considering physical characteristics and sense of physical burden. Moreover, the effectiveness was demonstrated by applying the proposed method to the problem of designing an appropriate work-table height. In the future, in order to derive design solution sets reflecting the physical characteristics of more users, comprehensive evaluation of the whole body, rather than just the waist and shoulder, must be considered, including such parameters as the angle of the elbow joint. Furthermore, since the load on the body increases with working time, it is necessary to consider changes in physical burden feeling over time using a DHM.

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